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A Literature Review on Bounding Flight in Birds with Applications to Micro Uninhabited Air Vehicles

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ABSTRACT

Bounding flight is an intermittent flight pattern adopted by birds, which may have applications for micro uninhabited air vehicle designs. In this report, a literature review has been undertaken to determine the reason for birds adopting this flight pattern. Four hypotheses are discussed, and a detailed reference list is provided.

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A Literature Review on Bounding Flight in Birds with Applications to Micro Uninhabited Air Vehicles

EXECUTIVE SUMMARY

Bounding flight is an intermittent flight pattern observed in small birds, in which periods of flapping flight alternate with periods of wings-folded flight. It has been suggested that this flight pattern could be adopted by micro uninhabited air vehicles (μUAV) to improve their flight characteristics. In response to this suggestion, a literature review of the bounding flight of birds has been undertaken.

Many authors have attempted to explain why birds adopt bounding flight. Hypotheses include the possibility that bounding flight is aerodynamically more efficient than continuous flapping, level flight; that bounding flight is used to counter a chemical imbalance in the flight muscles; or that bounding flight forms a compromise between aerodynamic and muscular constraints. These hypotheses are based on mainly circumstantial evidence. Birds have been observed to bound at a range of airspeeds, during both short and long range flights, and while hovering. However, no single hypothesis is adequate to explain bounding flight over all of these flight regimes. It is possible that an alternate explanation exists.

While not sufficient to explain all observations of bounding flight in birds, the suggested hypotheses may have applications for μUAVs. In particular, the suggestion that bounding flight is aerodynamically more efficient than level flight could potentially be exploited in the design of a μUAV. Improvements in the flight characteristics of μUAVs, potentially through the adoption of bounding flight, will be an important step towards the development of an operational μUAV for use in defence applications.

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Hilary Keating graduated from the University of Sydney in 1998, having obtained a Bachelor of Engineering in Aeronautical Engineering with first class honours. She commenced employment at AMRL in 1999, and has been involved in aircraft flight dynamic and performance modelling.

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AOD	Air Operations Division.
DARPA	Defense Advanced Research Projects Agency (US).
DSTO	Defence Science and Technology Organisation.
μUAV	Micro Uninhabited Air Vehicle.

Notation

a	Fraction of time a bird flaps its wings during a cycle of bounding flight (0 - 1).
A	Lift-independent power constant for a particular aircraft or bird at a particular flight condition.
B	Lift-dependent power constant for a particular aircraft or bird at a particular flight condition.
C_{D_o}	Lift-independent drag coefficient.
g	Gravity.
K	Lift-dependent drag coefficient.
L	Lift.
m	Mass.
P	Power.
$\bar{P}$	Mean power required for a cycle of bounding flight.
S	Reference area.
V	Airspeed.

Symbols

ρ	Air density.

Subscripts

b	Body.
$powered$	Powered phase (flapping).
md	Minimum-drag.
opt	Optimum.
$passive$	Passive phase (wings-folded).
w	Wing.

1 Introduction

In recent years, there has been a developing interest in uninhabited air vehicles, particularly micro uninhabited air vehicles (μUAV). μUAVs are generally defined as aerial vehicles whose linear dimensions do not exceed 150 mm in any one direction. It is envisaged that these vehicles will be used in a range of defence applications in the future, including reconnaissance, communication and surveillance missions. The US Defense Advanced Research Projects Agency (DARPA) has a program to design and develop a μUAV. With a funding of US$35 million between 1997 and 2001 [1], the DARPA program has planned a flight vehicle demonstration during 2003.

μUAVs are not simply smaller versions of currently operated aircraft. Due to their size and speed, μUAVs will operate at low Reynolds numbers, of the order of 10^4; a regime which until recently has been exclusive to small birds and large insects. In comparison, general aviation aircraft operate at Reynolds numbers of the order of 10^6 and above. Consequently, the development of a μUAV presents a number of challenges for designers, and significant technological developments will be required before their operation is possible.

Morris, a μUAV designer, has suggested that the lift-to-drag characteristics and handling qualities of μUAVs are design areas requiring improvement [2]. μUAV designs reviewed by Morris had poor lift-to-drag characteristics and handling qualities at high speed due to their large wing area [2]. A large wing area is required for manoeuvrability, however, for a given aircraft weight, this results in a low wing loading, causing an increased sensitivity to gust and control inputs, as well as decreased range and endurance [2, 3]. Morris has suggested that a solution to this problem may be found in nature; in particular, he suggests that a flight pattern found in birds, known as bounding flight, could have applications for μUAV designs. In response to this suggestion, a literature review has been undertaken to determine the reason for birds adopting bounding flight. The literature review is outlined in this report.

2 Bounding Flight in Birds

Bounding flight is an intermittent flight pattern in which a bird alternates between powered or flapping flight, and passive flight where its wings are folded against its body. When adopting this flight pattern, a bird will rise and fall in altitude following a flight path similar to that shown in figure 1. Bounding flight is also referred to as leaping or swooping flight [4, 5].

While bounding flight has been suggested to be the most widespread of all intermittent flight patterns in nature [6], it has only been observed in small birds. Birds adopting bounding flight generally have relatively large area, low aspect ratio wings with rounded wing tips [5, 7]. Such birds include small passerines (*Passeriformes*), small parrots (*Psittaciiformes*) and small owls (*Strigiformes*) [5, 8], with the green woodpecker (*Picus viridis*) being the largest bird observed to use this flight style [5, 9, 10, 11, 12]. Bounding flight has not been observed in bats [5].

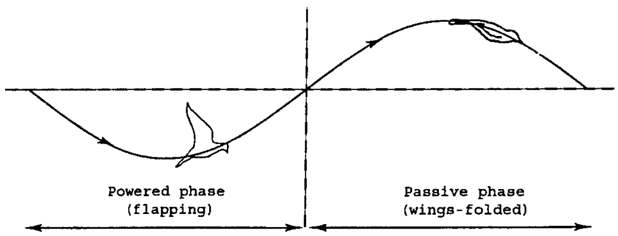

Figure 1: Flight path of bounding flight.

The flight patterns of birds are likely to have evolved as a compromise between physical limitations and a need to minimise the energy expenditure of flight [5, 10]. Many authors have attempted to explain why birds adopt bounding flight instead of continuous flapping, level flight and four hypothesis are discussed in the following sections.

2.1 Aerodynamic Efficiency Hypothesis

Flight performance models of birds during bounding flight have been developed by Alexander [10], DeJong [13], Furber (in Lighthill) [4], Rayner [5, 11] and Ward-Smith [6, 9, 12]. While these mathematical models differ, the conclusions drawn by each author on the benefits of bounding flight are similar. The flight performance model developed by Alexander and extended by Rayner is presented here. In this analysis, airspeed is assumed constant. This assumption is supported by studies of small estrildid finches (*Estrildidae*), where the variation of airspeed over a cycle of bounding flight was observed to be small [5].

Alexander shows that the mean power required for a cycle of bounding flight is:

$$\bar{P} = A_b V^3 + a A_w V^3 + \frac{Bm^2 g^2}{aV} \tag{1}$$

where a is the fraction of time the bird flaps its wings during a cycle of bounding flight, V is the airspeed, $A_b V^3$ is the lift-independent power requirement associated with the movement of the bird's body through the air, $A_w V^3$ is the lift-independent power requirement associated with the wings during the powered phase and $\frac{Bm^2g^2}{aV}$ is the lift-dependent power required to maintain a level flight path.

From equation 1, Rayner demonstrates that an energy saving can only be achieved from bounding flight if:

$$V > V_{md}(1 + \frac{A_b}{A_w})^{\frac{1}{4}} \tag{2}$$

where V_{md} is the maximum range (minimum-drag) airspeed. A detailed derivation of equation 2 is given in appendix A.

The value of $\frac{A_b}{A_w}$ is likely to be between 0.5 and 2 and therefore a bird must fly faster than about $1.2V_{md}$ to obtain an advantage from bounding flight [5]. As shown in appendix A, as the airspeed increases, a bird should flap its wings for a smaller fraction of time. Consequently, very fast flight requires a high power output from the flight muscles during the short bursts of flapping [5, 10] and the upper constraint on V is therefore determined by the maximum power output from the flight muscles [5].

While bounding flight in birds can be shown to be mathematically advantageous at airspeeds greater than $1.2V_{md}$ using the simple parabolic drag performance model, bird observations do not support this conclusion for a number of reasons. The above analysis of bounding flight could be applied to all flying bird and bats, although bounding flight is only observed in small birds. Additionally, birds are observed to use bounding flight at airspeeds less than V_{md} and in hovering [5, 14], and have also been found to bound over short distances [5] where the aerodynamic benefits would be negligible [11]. Over long flights, such as during bird migration, bounding flight offers no power saving over continuous flight at V_{md} [5]. Therefore, migrating birds would not be expected to adopt bounding flight, but frequently do so [5, 14].

2.2 Chemical Imbalance Hypothesis

Rayner notes that other authors [15, 16] have suggested a chemical imbalance as an explanation of bounding flight [5]. This hypothesis proposes that the passive phase of bounding flight is used as a recovery period from the powered phase during which a chemical imbalance occurs in the flight muscles. This hypothesis is supported by the finding that chemical cycling occurs in fish during burst swimming [17], however, Rayner argues that the passive phase of bounding flight is too short to be useful in chemical recovery [5].

2.3 Fixed Power Output Hypothesis

Several authors have suggested that bounding flight forms a compromise between aerodynamic performance and muscular constraints [5, 11, 14, 18]. In order to reduce their body mass, small birds have evolved to carry muscles with only a limited number of fibres [5] which restricts their power output to a single, fixed level per wingbeat [14]. Furthermore, experiments have shown that the flight muscles of birds only produce maximum power within a narrow band of contraction rates, so regulation of airspeed by varying wingbeat frequency is inefficient [6, 12, 14]. If this is the case, small birds are restricted to a fixed power output. This must be the maximum continuous power output, required for take-off, acceleration and steep climbing flight [5, 19]. By flapping intermittently, as during bounding flight, small birds are able to achieve a lower mean power output and a wide range of airspeeds while maintaining high muscular efficiency [5, 6, 12, 14].

The fixed power output hypothesis[1] is supported by observations of bounding flight in small birds during both short and long flights, and at speeds less than V_{md}. However, Tobalske notes that budgerigars (*Melopsittacus undulatus*) flap continuously during hovering flight

[1]This hypothesis is referred to as the 'fixed-gear' hypothesis in the literature and has been renamed here to avoid confusion with standard aircraft terminology.

and bound during forward flight [14]. Tobalske accounts for this discrepancy by suggesting that the fixed power output hypothesis may only apply to very small birds with low aspect ratio wings. In contrast, budgerigars are considerably larger than the smallest birds found to adopt bounding flight and have long pointed wings. According to Rayner, large birds have a more flexible muscle geometry and their power outputs are therefore not restricted in the same way as small birds [11].

2.4 Body-Lift Hypothesis

The body-lift hypothesis proposes that bounding flight is aerodynamically advantageous due to the generation of a partial weight-supporting force [5, 14] during the passive phase. Rayner suggests that the term 'body-lift' is misleading and that the weight-supporting force may be a vertical component of drag generated at high body incidence angles [5]. He further suggests that this force may act throughout the flight, but is largest during the passive phase.

The weight-supporting force, predicted by the body-lift hypothesis, is likely to reduce altitude losses and increase range during the passive phase [20, 21]. Weight-supporting forces were measured by Tobalske during wind tunnel tests of zebra finches (*Taenopygia guttata*) [14]. From these experiments, Tobalske concluded that the body-lift hypothesis was adequate to explain bounding flight at moderate to fast speeds but not at low airspeeds or during hovering flight. The restriction of this hypothesis to small birds was not found to be discussed in the literature.

2.5 Overview

The four hypotheses presented in the previous sections are mainly circumstantial and no one hypothesis is adequate to explain bounding flight in birds for all airspeeds. Rayner suggests that bounding flight may not only be a means of reducing mechanical energy demands and the possibility of an alternative physiological explanation can not be ruled out [5].

3 Applications for Micro Uninhabited Air Vehicles

While the exact reason for bounding flight in birds is unclear, the hypotheses explaining the adoption of this flight pattern by birds may have applications for μUAV designs. Morris has suggested that a μUAV design with a stowable wing would be capable of adopting bounding flight [2]. Such a design could effectively increase its wing loading during high speed cruise, thus improving the lift-to-drag characteristics and handling qualities. The design suggested by Morris is shown in figure 2, however, further designs using fixed, flapping or variable-sweep wings are possible.

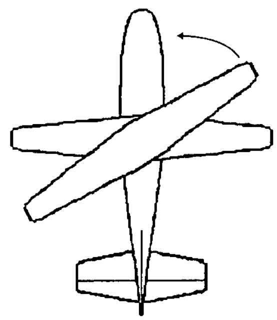

Figure 2: μUAV design with stowable wing [2].

Based on the mathematical analysis presented in section 2.1, a μUAV capable of adopting bounding flight could potentially cruise at high speed with a similar power requirement to continuous flight at V_{md}. Furthermore, Morris has suggested that bounding flight would result in little reduction in range or manoeuvrability [2]. Increasing the cruise speed of the vehicle has the advantage of allowing it to operate in a higher Reynolds number regime, as well as reducing the time required to reach the target station.

The fixed power output hypothesis may also have applications for μUAV designs. For example, a μUAV design with an electric motor was reviewed by Morris [2]. The electric motor was found to operate efficiently only at high RPM [2]. Coupled with a fixed pitch propeller, such a μUAV could be constrained to a fixed power output, similar to a small bird. In this case, bounding flight would provide various level flight speeds, while maintaining high motor efficiency.

Additional applications of bounding flight for μUAV designs are likely and further research is required. This research could involve a feasibility study into the construction of a μUAV capable of bounding flight, a more detailed flight performance analysis to determine the improvement in aerodynamic efficiency during high speed cruise and the possible variation in range, a parameter estimation study to assess the handling qualities, and the design of a bounding flight manoeuvre controller.

This research could be extended to include an investigation into other flight patterns of birds, including undulating flight. Undulating flight is similar to bounding flight, with the exception that the birds wings remain extended during the passive phase. If undulating flight was found to have a performance benefit, this flight pattern could result in a simpler μUAV design by removing the necessity for the wings to be folded during the passive phase.

4 Conclusion

A literature review of a flight pattern found in birds, known as bounding flight, has been undertaken. Four hypotheses have been discussed, however, no one hypothesis was found to adequately explain the reason for birds adopting bounding flight at all airspeeds. Bounding flight may have applications for improving the flight performance and handling qualities of μUAVs, however, further research will be required to assess the potential benefits.

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Appendix A: Flight Performance Model of Bounding Flight in Birds

Flight performance models of birds during bounding flight have been developed by several authors [4, 5, 6, 9, 10, 11, 12, 13]. The model developed by Alexander [10] and Rayner [5] is given here.

The parabolic drag polar assumption of power required, P, by a fixed wing aircraft for level flight at an airspeed, V, is:

$$P = (\frac{1}{2}\rho C_{D_o} S)V^3 + (\frac{2KL^2}{\rho S})\frac{1}{V} \tag{A1}$$

This equation can be simplified to:

$$P = AV^3 + (BL^2)\frac{1}{V} \tag{A2}$$

where A and B are constants for a particular aircraft at a particular flight condition.

According to Alexander [10], equation A2 can be applied to the flapping flight of birds with minimal error. The body and wing components of the lift-independent drag are separated, as follows.

$$P = (A_b + A_w)V^3 + (BL^2)\frac{1}{V} \tag{A3}$$

During bounding flight, a bird flaps its wings for a fraction of the time, denoted as a. By definition, a is a value between 0 and 1, however, values close to 1 are unlikely [5]. To maintain level flight, the mean lift of the bird must be equal to its weight. It is assumed that lift is not generated during the passive phase and consequently the lift required during the powered phase is $\frac{mg}{a}$. This assumption appears to have been made for the simplicity of the analysis and does not account for body-lift generated during the passive phase.

The power required during the powered phase is:

$$P_{powered} = (A_b + A_w)V^3 + (\frac{Bm^2g^2}{a^2})\frac{1}{V} \tag{A4}$$

During the passive phase when the wings are folded, the wing drag and the lift are assumed to be zero. Hence,

$$P_{passive} = A_b V^3 \tag{A5}$$

The mean power for a cycle of bounding flight is therefore,

$$\begin{aligned}\bar{P} &= aP_{powered} + (1-a)P_{passive} \\ &= (A_b + aA_w)V^3 + (\frac{Bm^2g^2}{a})\frac{1}{V}\end{aligned} \tag{A6}$$

By differentiation of equation A6, a value of a which minimises the power needed for flight can be determined.

$$\frac{d\bar{P}}{da} = A_w V^3 - (\frac{Bm^2g^2}{a^2V}) \tag{A7}$$

The optimum value of a occurs when the derivative $\frac{d\bar{P}}{da}$ is zero. Therefore,

$$a_{opt} = (\frac{B}{A_w})^{\frac{1}{2}}(\frac{mg}{V^2}) \tag{A8}$$

(In this case, $\frac{d^2\bar{P}}{da^2}$ is positive and $\bar{P}$ is a minimum.)

Rayner [5] shows that the maximum range (minimum-drag) airspeed, V_{md}, for continuous flapping flight is:

$$V_{md} = (\frac{B(mg)^2}{A_b + A_w})^{\frac{1}{4}} \tag{A9}$$

Therefore, equation A8 can be re-written as:

$$a_{opt} = (1 + \frac{A_b}{A_w})^{\frac{1}{2}}(\frac{V_{md}}{V})^2 \tag{A10}$$

Analysis of equation A10 shows that as the airspeed increases, a bird should flap its wings for a smaller fraction of time. Additionally, since bounding flight is only possible if $a < 1$, equation A10 implies an energy saving can only be achieved if:

$$V > V_{md}(1 + \frac{A_b}{A_w})^{\frac{1}{4}} \tag{A11}$$

The value of $\frac{A_b}{A_w}$ is likely to be between 0.5 and 2 and therefore, a bird must fly faster than about $1.2V_{md}$ to obtain an advantage from bounding flight [5].

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19. ABSTRACT

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